A New Way to Measure Spin at Hadron Colliders

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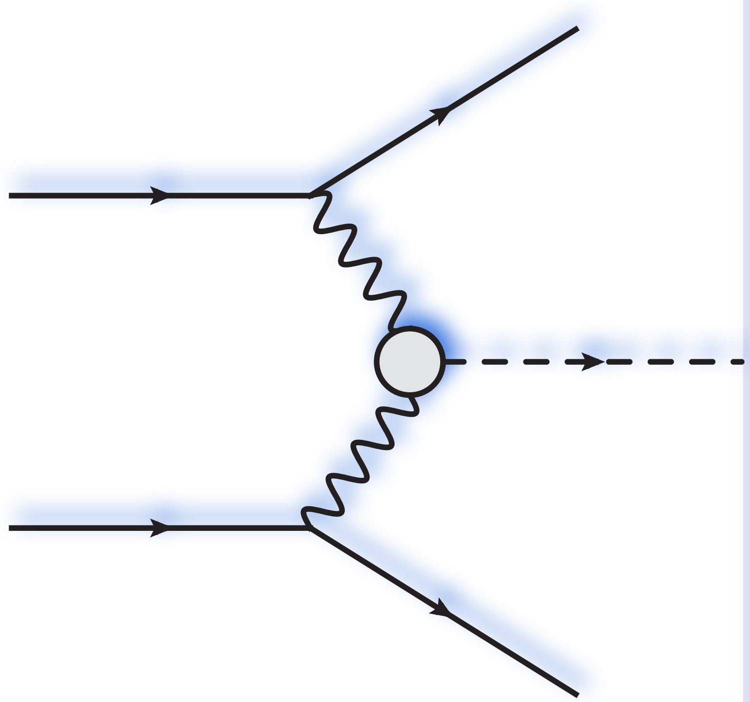
Spin Determination

- Many SM extensions contain new strongly interacting particles that decay into SM + missing energy
- Spin measurements key to distinguishing possibilities
- Ideally, want a technique that doesn't rely on long decay chains, chiral couplings, or decays into specific final states.

Inspiration from Higgs Search

- Proposal from Zeppenfeld *et. al.*
- Consider on-shell Higgs production from Vector Boson Fusion (VBF)

  - Azimuthal angular dependence comes from gauge boson helicity
  - Presence of various cos/sin modes depends on how these helicities can be combined.

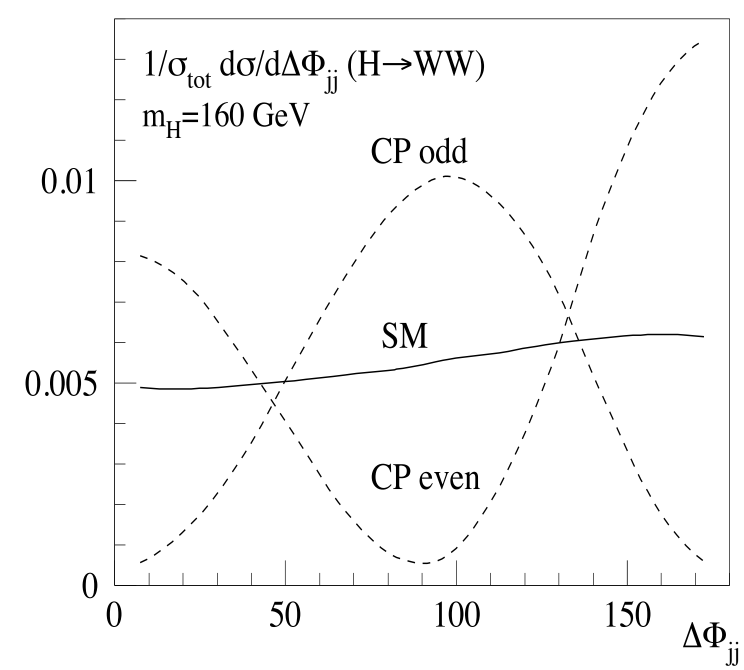


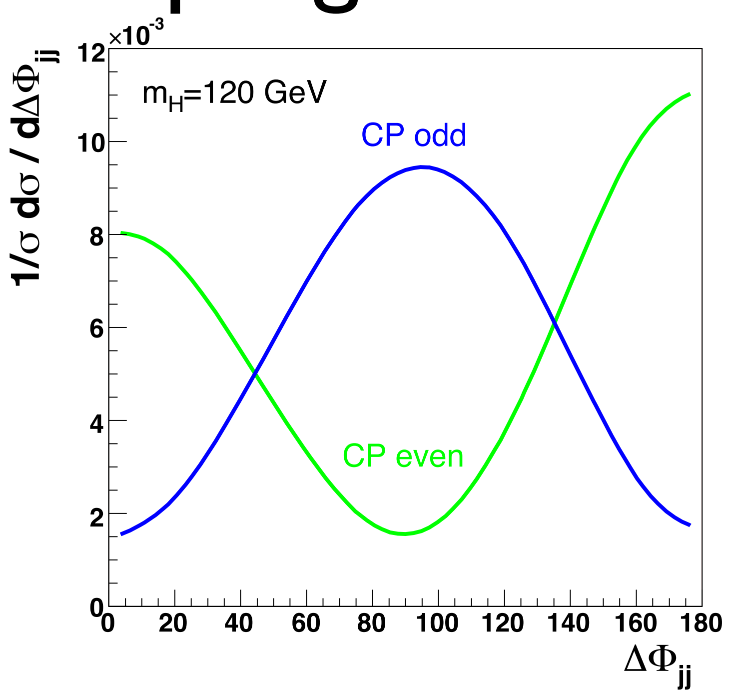
  - *i.e.* on the Lorentz structure of the matrix element for Higgs production

hep-ph/0105325, hep-ph/0605117, hep-ph/0703202

Inspiration from Higgs Search

- Searches for invisible Higgs decay
  - Look for azimuthal angular correlations in forward jets
  - Also shown that $d\sigma/d\Delta\phi$ sensitive to CP-properties of Higgs coupling





  - Background has no $\cos 2\Delta\phi$ mode

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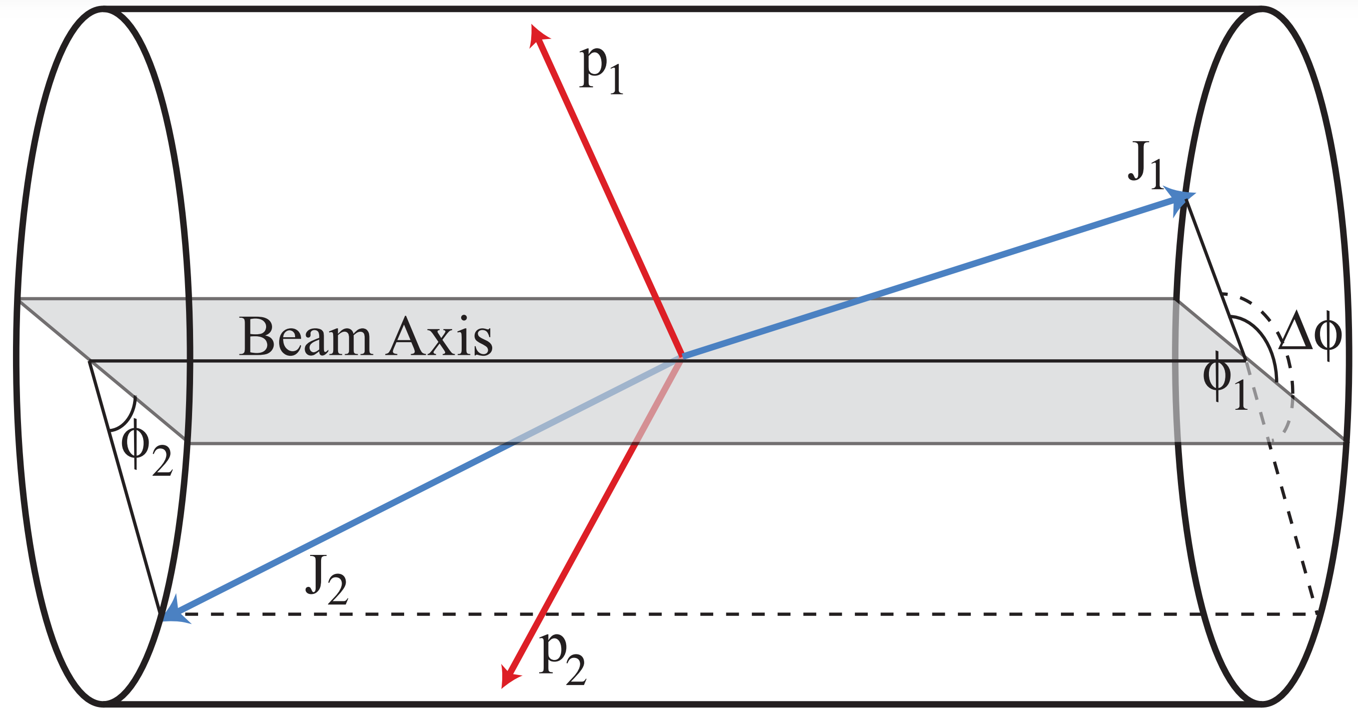
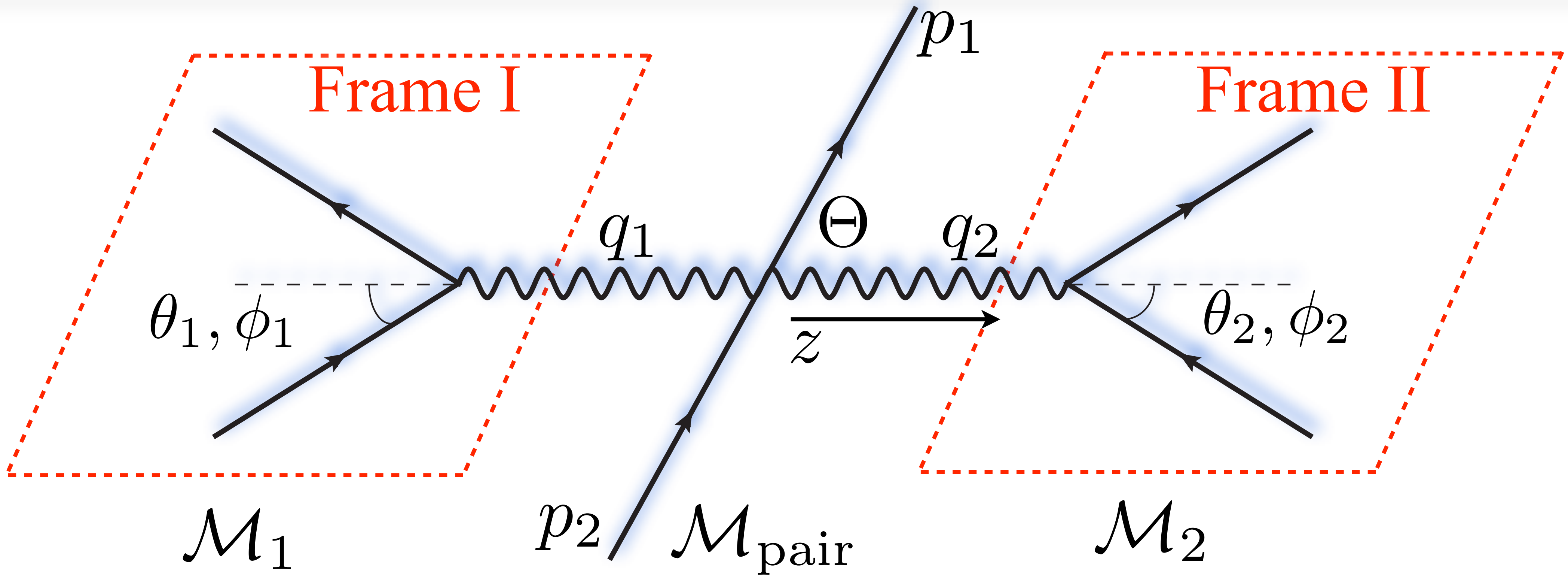
The Big Picture



- Since the spin measurement relies on the kinematics of jets J_1/J_2 , the only requirements on new physics (p_1/p_2) is that we can trigger on it (and identify the forward jets)
- For this introductory study, we assume both these problems can be ignored
  - Clearly, we are not experimentalists.

VBF Kinematics



- With these choices, ϕ dependence made clear:

$$\epsilon_{1/2} \propto e^{+i\phi_{1/2}}, e^{-i\phi_{1/2}}, e^{0\times i\phi_{1/2}}$$

- I've drawn quark initial states only, but anti-quark and gluon contribute as well.

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Saturday, August 27, 2011

Azimuthal Angular Dependence

- Can expand out dependence on ϕ_1, ϕ_2 :

$$|\mathcal{M}|^2 = \left| \sum_{h_1, h_2 = \pm, 0} \mathcal{M}_1 \mathcal{M}_2 \mathcal{M}_{\text{pair}} e^{i(h_1\phi_1 + h_2\phi_2)} \right|^2$$

$$|\mathcal{M}|^2 \propto A_0 + A_1 \cos\Delta\phi + A_2 \cos 2\Delta\phi$$

After integrating over $\phi_1 + \phi_2$

A_2

- The coefficient A_1 gets a contribution from cuts.
- Look at the coefficient of $\cos 2\Delta\phi$ instead.
  - From

$$|\mathcal{M}|^2 = \left| \sum_{h_1, h_2 = \pm, 0} \mathcal{M}_1 \mathcal{M}_2 \mathcal{M}_{\text{pair}} e^{i(h_1\phi_1 + h_2\phi_2)} \right|^2$$

we're interested in

$$A_2 = (\mathcal{PS}) \sum_{\substack{h_1, h_1', h_2, h_2' \\ |h_i - h_i'| = 2}} (\mathcal{M}_1(h_1)\mathcal{M}_2(h_2)\mathcal{M}_{\text{pair}}(h_1, h_2)) \times (\mathcal{M}_1(h_1')\mathcal{M}_2(h_2')\mathcal{M}_{\text{pair}}(h_1', h_2'))^*$$

Scalar Case

- Factoring out production matrix elements:

$$\begin{aligned} A_2 &= (\mathcal{PS})\mathcal{M}_1(+1)\mathcal{M}(-1)^*\mathcal{M}_2(-1)\mathcal{M}_2(+1)^* \\ &\quad [\mathcal{M}_{\text{pair}}(+1,-1)\mathcal{M}_{\text{pair}}(-1,+1)^* + (+1 \leftrightarrow -1)] \end{aligned}$$

- In an abelian theory, easy to write down the matrix elements for transverse polarizations:

$$\mathcal{M}_{\text{scalar}} \propto (\epsilon_1 \cdot \epsilon_2) - 4\left[\frac{(p_1 \cdot \epsilon_1)(p_1 - q_1)\cdot \epsilon_2}{q_1^2 - 2p_1 \cdot q_1} + \frac{(p_1 \cdot \epsilon_2)(p_1 - q_2)\cdot \epsilon_1}{q_2^2 - 2p_1 \cdot q_2}\right]$$

- Invariant under $\epsilon^+_{1/2} \leftrightarrow \epsilon^-_{1/2}$
  - (Also true in non-abelian calculation)

$$\boxed{A_2 \propto \mathcal{M}(+1,-1)\mathcal{M}(-1,+1)^* > 0}$$

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Spinor Case

- Straightforward for on-shell abelian example:

$$\mathcal{M}(\pm 1, \mp 1) = i\bar{u}\left[\frac{\not{\epsilon}_1^{\pm}(\not{p}_1 - \not{q}_1 + M)\not{\epsilon}_2^{\mp}}{q_1^2 - 2p_1\cdot q_1} + \frac{\not{\epsilon}_2^{\mp}(\not{p}_1 - \not{q}_2 + M)\not{\epsilon}_1^{\pm}}{q_2^2 - 2p_1\cdot q_2}\right]v$$

$$A_2 \propto -\frac{64m^2}{s}\left(1 + \frac{4m^2}{s\sqrt{1-4m^2/s}}\tanh^{-1}\sqrt{1-4m^2/s}\right) < 0$$

- Non-abelian example more subtle.
- Can divide $\mathcal{M}(+1,-1)\mathcal{M}(-1,+1)^*$ into symmetric ($d_{abc}d_{abd}T^cT^d$) and antisymmetric ($f^{abc}f^{abd}T^cT^d$) parts
  - Symmetric part reproduces abelian $A_2 < 0$
  - Asymmetric part naively gives $A_2 > 0$

Spinor Case

- Naive calculation ignores phase space cuts experimentally necessary to isolate VBF diagrams
  - (also not gauge invariant, as we calculate only VBF diagrams, not the full 1000+ possible)
- After cuts, isolating events with fusing gluons that are space and spin symmetric. Thus color-antisymmetric states don't contribute.

  - Simulation through Calchep and MadGraph confirm that, for spinors,

$$A_2 < 0$$

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Simulation Results

- Use MadGraph/MadEvent for background-free simulation:

$$pp \to 2(\mathrm{R-hadrons}) + jj$$

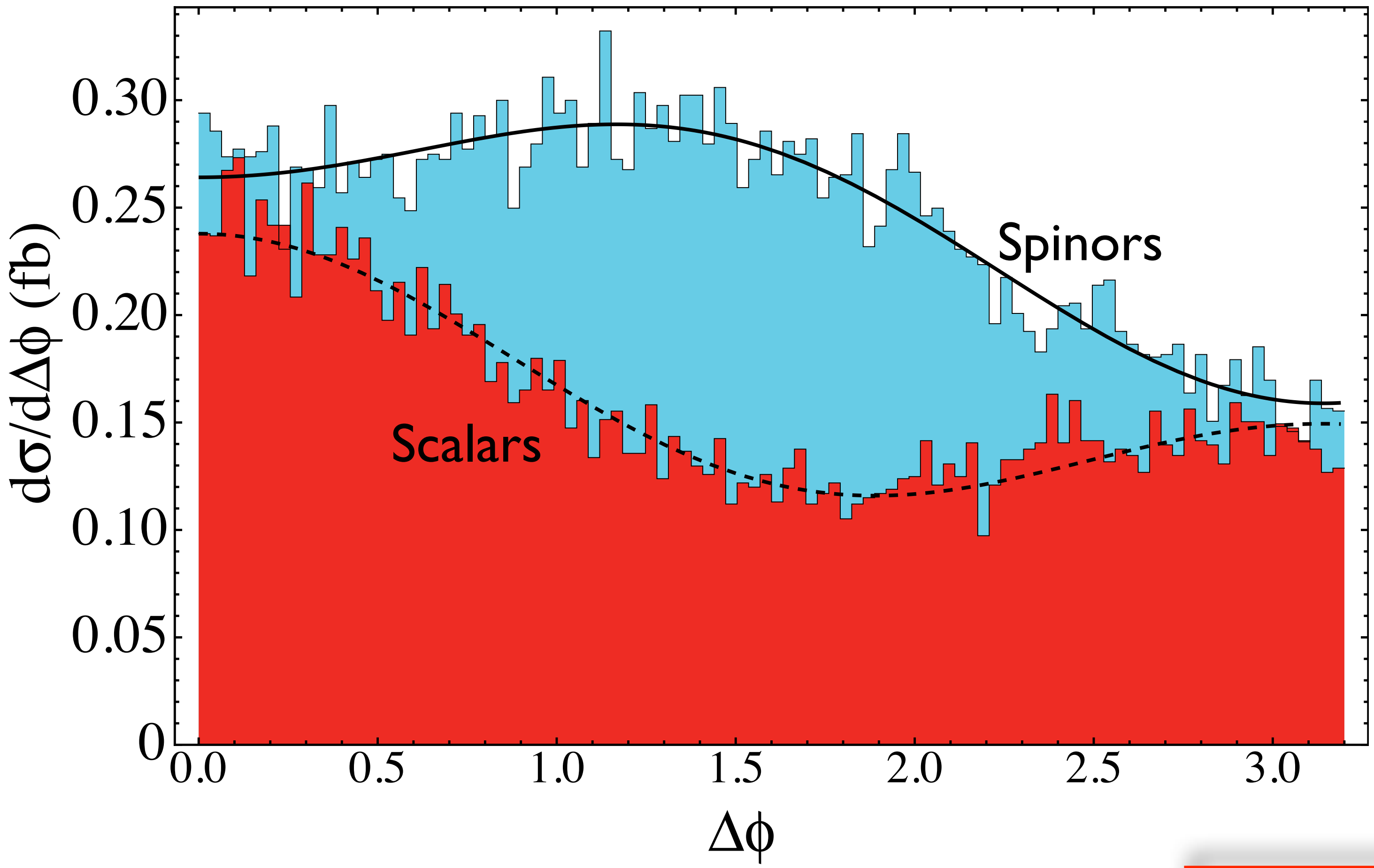
- 500 GeV R-hadrons (excluded by Lepton/Photon)
- Apply VBF-isolating cuts:

$$\eta_{j_1} \cdot \eta_{j_2} < 0,\ |\eta_j| \leq 5,\ |\eta_{j_1} - \eta_{j_2}| \geq 4.2$$
$$p_{T,j_1} \geq 30\ \mathrm{GeV},\ p_{T,j} \geq 20\ \mathrm{GeV},\ M_{jj} \geq 500\ \mathrm{GeV}$$
$$|\eta_{R-\mathrm{hadron}}| < 2.1,\ \ p_{T,R-\mathrm{hadron}} > 50\ \mathrm{GeV}$$

- Total cross section ($\sqrt{s} = 10\ \mathrm{TeV}, m = 500\ \mathrm{GeV}$):

$$\sigma_{\mathrm{spinor}} = 33\ \mathrm{fb}, \sigma_{\mathrm{scalar}} = 21\ \mathrm{fb}$$

Results



$$\frac{d\sigma_{\rm scalar}}{d\Delta\phi} = 0.16 + 0.044\cos\Delta\phi + 0.035\cos 2\Delta\phi \quad \text{(fb)}$$

$$\frac{d\sigma_{\rm spinor}}{d\Delta\phi} = 0.24 + 0.053\cos\Delta\phi - 0.033\cos 2\Delta\phi \quad \text{(fb)}$$

$$\boxed{\begin{array}{c} (A_2/A_0)_{\rm scalar} = 0.22 \\ \\ (A_2/A_0)_{\rm spinor} = -0.14 \end{array}}$$

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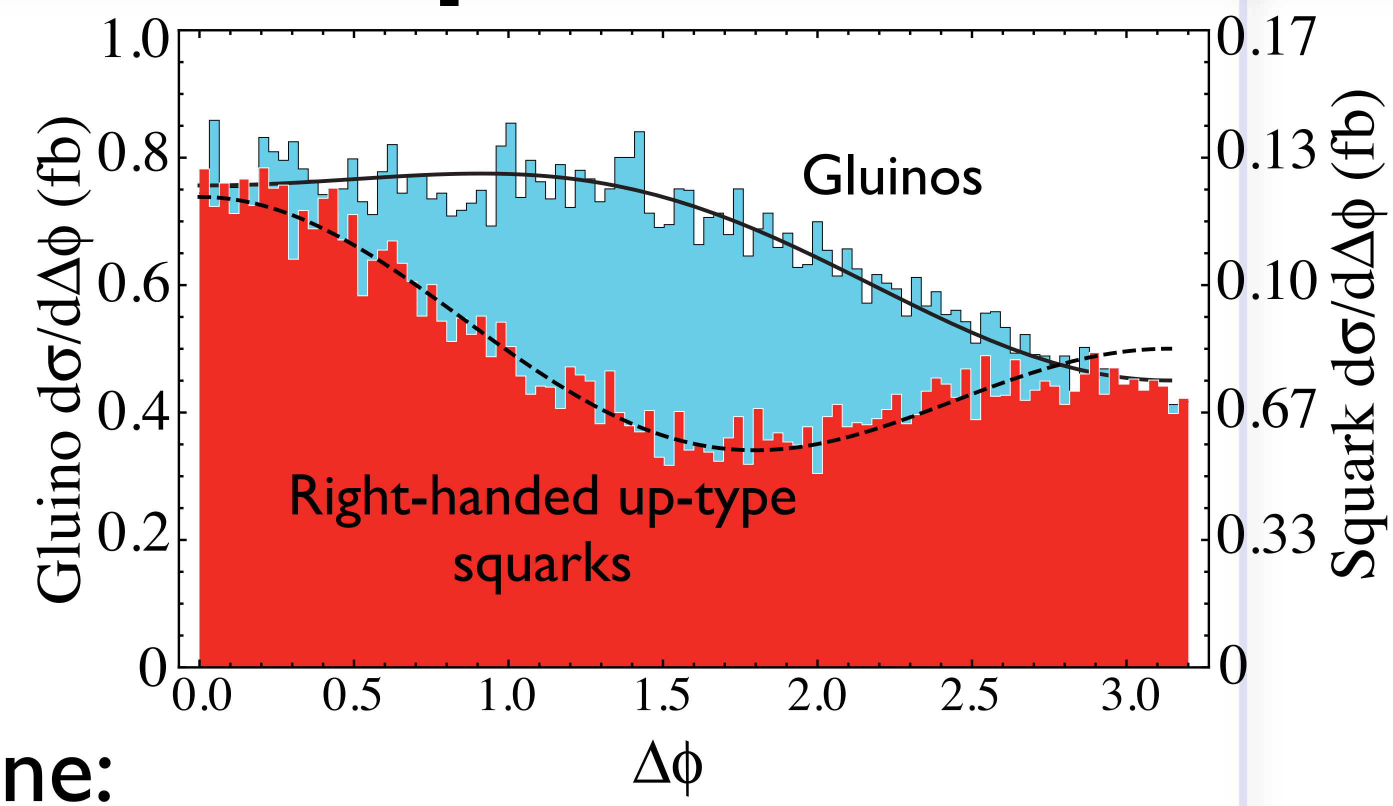
SUSY Applications

- We picked a "background free" model
  - No central jets that can be confused with the forward jets that constitute our observables
- Obvious next step: SUSY gluino pairs/squark pairs

- What we have done:
  - Background-free, trigger/tagging free MadGraph study (*i.e.* is there a signal?)

Gluinos and Squarks



- Demonstrates that a signal is present, and that the majorana nature of the gluinos isn't a problem.
- What needs to be done:
  - Background (naive expectation: flat in $\cos 2\Delta\phi$)
  - Trigger analysis, cut optimization
  - Jet ID, including decays of gluinos/squarks

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Problems with Pythia

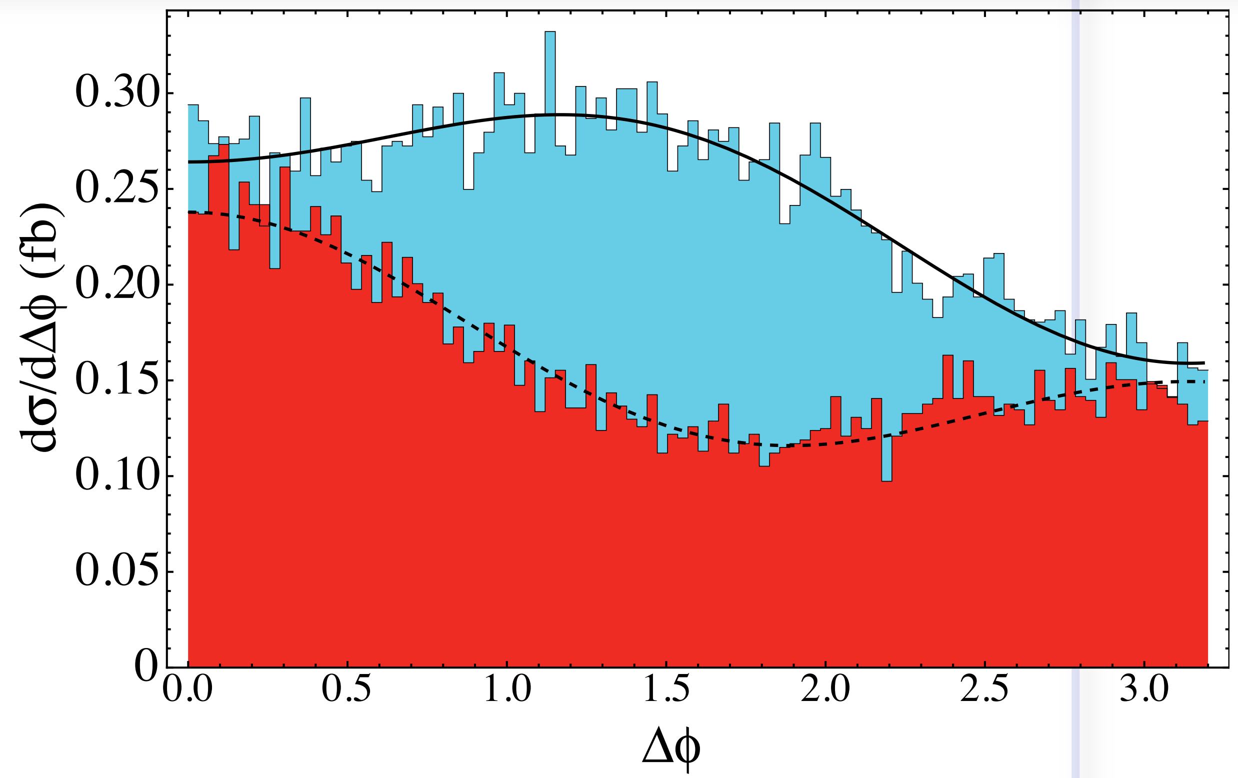
- Background analysis (including decays) requires simulation with Pythia, as our signal relies on forward jets
- However, Pythia-generated jets do not include helicity information
  - MadGraph does, but the overall cross-section is wrong (no matching)
- Therefore, we claim that simulation of forward jets does not include correlations which contain useful physics information!

Future Work

- Understand how to correctly integrate MadGraph and Pythia results in the forward region
  - Also a useful test of the effect on cuts on $\Delta\phi$ distributions
- Optimize cuts to for signal & cross section
- Test at LHC using $t\bar{t}$ production?
- Examine vector pair production
- Look for physics information in $\phi_1 + \phi_2$ coefficients

Conclusions

- Correlations in forward jets originating in VBF events contain useful information about spin
- Allows a "model-independent" measurement



- This work reveals a kinematic region where existing simulation tools are inadequate
  - Important information can exist in angular correlations, but not all simulators include these.